# Stability Analysis of Intertank Formed Skin/Stringer Compression Panel with Simulated Damage

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*Extended Abstract of Proposed Paper for the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 23-26, 2012, Honolulu, Hawaii*

*Category: Structures*

## Introduction

The External Tank (ET) is a component of the Space Shuttle launch vehicle that contains fuel and oxidizer. During launch, the ET supplies the space shuttle main engines with liquid hydrogen and liquid oxygen. In addition to supplying fuel and oxidizer, it is the backbone structural component of the Space Shuttle. It is comprised of a liquid hydrogen (LH2) tank and a liquid oxygen (LOX) tank, which are separated by an Intertank. The Intertank is a stringer-stiffened cylindrical structure with hat-section stringers that are roll formed from aluminum-lithium alloy Al-2090.

Cracks in the Intertank stringers of the STS-133 ET were noticed after a November 5, 2010 launch attempt. The cracks were approximately nine inches long and occurred on the forward end of the Intertank (near the LOX tank), along the fastener line, and were believed to have occurred while loading the ET with the cryogenic propellants. These cracks generated questions about the structural integrity of the Intertank.

In order to determine the structural capability of the Intertank with varying degrees of damage, a finite element model (FEM) simulating a 1995 compression panel test was analyzed and correlated to test data. Varying degrees of damage were simulated in the FEM, and non-linear stability analyses were performed. The high degree of similarity between the compression panel and the Intertank provided confidence that the ET Intertank would have similar capabilities.

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## Background

In 1995 and 1996, tests were conducted on compression panels that were based on sections of the Super Lightweight Tank (SLWT) Intertank [1]. The tests incorporated flight-like thermal conditions and simulated thermal deflections at the LH2/Intertank interface (the location of the bounding compressive design loads). The test setup used an adjustable cryogenic base and rollers to achieve flight-like boundary conditions. The compression panel was 137.48 inches long, 33.2 inches wide, and is detailed in Figure 1. The test setup is shown in Figure 2.

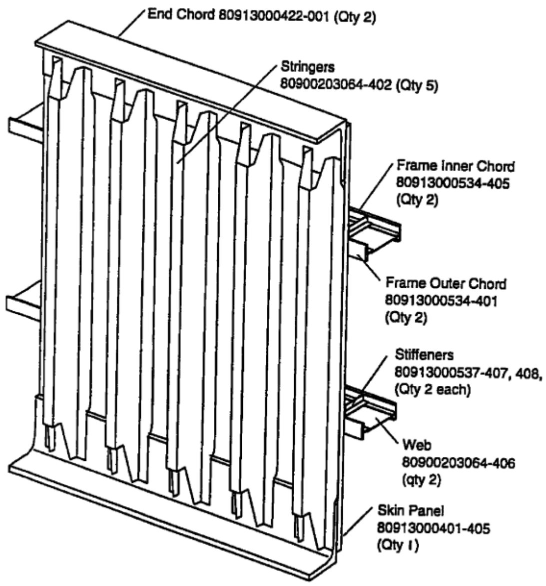


**Figure 1: Compression Panel Overview**

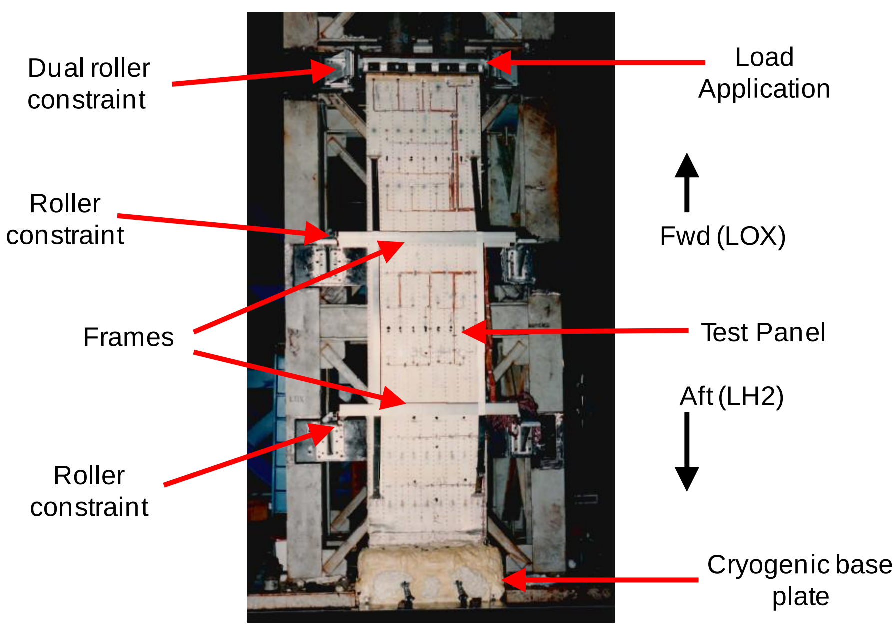


**Figure 2. Compression Panel Test Setup**

At the time this analysis was initiated, all the known cracks in the STS-133 ET were located at the LOX/Intertank interface. However, it was unknown if any cracks existed at the LH2/Intertank interface. Furthermore, because the most severe compressive loads occur at the LH2/Intertank interface, it was decided that analysis of this test article would be insightful for determining structural capability.

## Analysis

The compression panel FEM is shown in Figure 3 and is modeled primarily with shell elements. The fasteners are modeled as linear elastic beam elements, and fastener failure is not considered. Non-linear connector elements are modeled to simulate the roll ties included in the test setup (acting as springs in tension, but not carrying load in compression). Contact is simulated between stringers, frame chords, and the panel skin. Material plasticity is included in the skin, stringers, and a stiffening plate (doubler). The panel FEM and boundary conditions are modeled from drawings 80900203064 and 97M22728 [2, 3], which were provided by NASA.

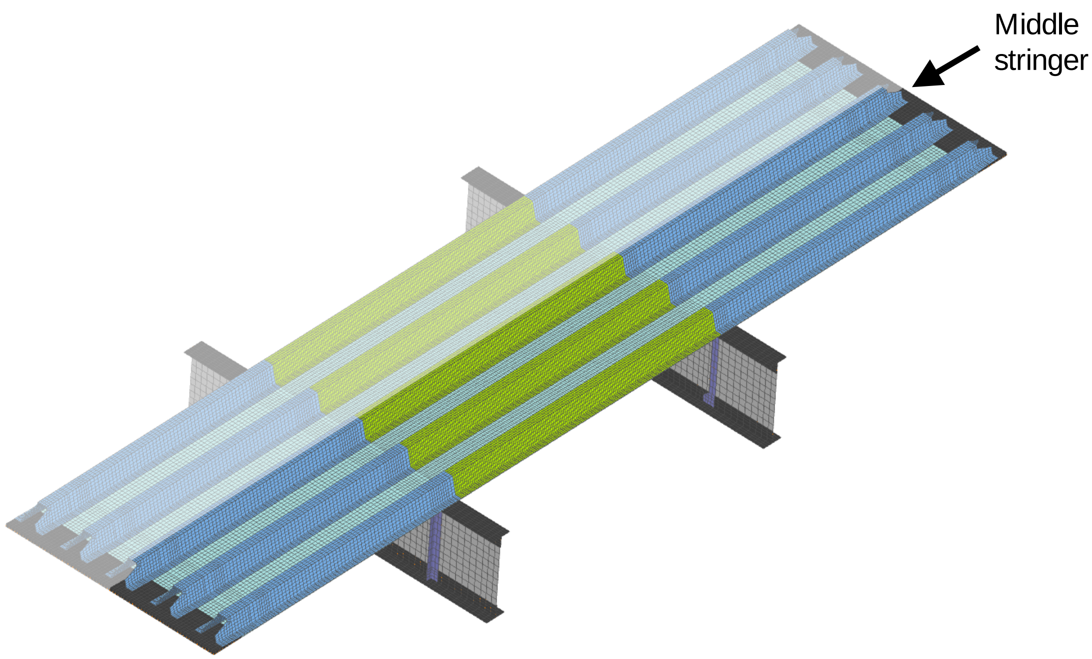


**Figure 3: Compression Panel FEM (symmetric elements shown as faded for clarity)**

The panel compressive load capability is predicted using an incremental, non-linear static solution procedure [4] in ABAQUS v6.9[3]. Several analysis steps are needed to adequately approximate the test through FEM analysis. The first step involves preloading the fasteners to ensure contact between stringers, skin, and frame chords. A second step applies thermal loads and simulates thermal displacement at the aft end of the

[3] ABAQUS is a registered trademark of Dassault Systèmes.

panel. A third step incrementally displaces the top of the panel to a load value just below the buckling load (~90%). The final step increases the displacement at the top of the panel FEM into the post-buckled region and implements static stabilization to aid in convergence.

The FEM is first analyzed based on the as-tested configuration. Once the FEM shows a high degree of correlation to the test data, the FEM is modified to be more flight-like. Modifications include modifying the skin thickness from 0.085 inches to 0.083 inches, removing the doubler plate on the aft end of the panel, and increasing the thermal deflection to 0.625 inches. An undamaged, pristine flight-like configuration is analyzed first to achieve a baseline result.

An out-of-family material behavior that was not controlled by the material acceptance requirements was determined to be a likely contributor to the crack failures. This out-of-family behavior was traced to stringers manufactured from two specific lots of Al-2090 sheet. The material properties of the stringers in the FEM are modified to match those of the “suspect” lots of Al-2090 based on test data.

A design limit load was provided by NASA and is used for fail-safe margin calculations based on Intertank limit loads for stringers S9-1 and S10-1, the highest loaded stringers on the Intertank.

Different degrees of damage are simulated by separating elements in the sections of the stringers where the cracks were observed on the STS-133 ET. Fastener elements were also separated from the stringer elements in the cracked area. Negative fail-safe margins were calculated for one of the damaged configurations involving cracks in multiple stringers. To determine whether the negative margins were driven by the large size of the damaged area with respect to the narrow panel width, an augmented FEM that was nine stringers wide was created to investigate size effects. All of the FEM configurations analyzed are described in Table 1.

## Results

The as-tested FEM correlates well with test data and closely matches the test failure mode. The global failure mode is shown in Figure 4.

The FEM strain predictions correlate very well with strain gage data and accurately predict the onset of skin buckling. The test setup did not measure the axial displacement of the panel, so correlation of FEM displacement cannot be determined. However, the load-displacement curve for the FEM is compared to the global failure load in Figure 5.

**Table 1: Panel FEM configurations analyzed**

| Study | Purpose |
|---|---|
| As-tested panel configuration | Baseline to correlate and anchor test data |
| Flight-like panel configuration | Flight-like baseline for comparison |
| Flight-like panel configuration with 7.3-inch cracks in both feet of the middle stringer extending to the first rivet | Fail-safe capability prediction for a compression test with one stringer degraded/damaged |
| Flight-like panel configuration with 12-inch cracks in both feet of the middle stringer | Fail-safe capability prediction for a compression test with one stringer degraded/damaged |
| Flight-like panel configuration with 7.3-inch cracks in both feet of the middle three stringers | Fail-safe capability prediction for a compression test with multiple stringers degraded/damaged |
| Flight-like panel configuration with short radius blocks on all stringers and no cracks in any stringer feet | Determine impact of radius blocks to global response and buckling capability of panel (Do-no-harm assessment) |
| Flight-like panel configuration with "foot-down" imperfection applied to the ends of the stringers | Determine impact of residual assembly stresses due to "foot-down" stringer imperfections to global response and buckling capability of panel |
| Augmented flight-like panel configuration (pristine) | Baseline for comparison with flight-like baseline |
| Augmented flight-like panel configuration with 7.3-inch cracks in both feet of the middle three stringers | Determine if the negative fail-safe margin observed in the flight-like panel configuration with cracks in both feet of the middle three stringers was due to number of remaining stringers to take load, or is a truly negative fail-safe margin |

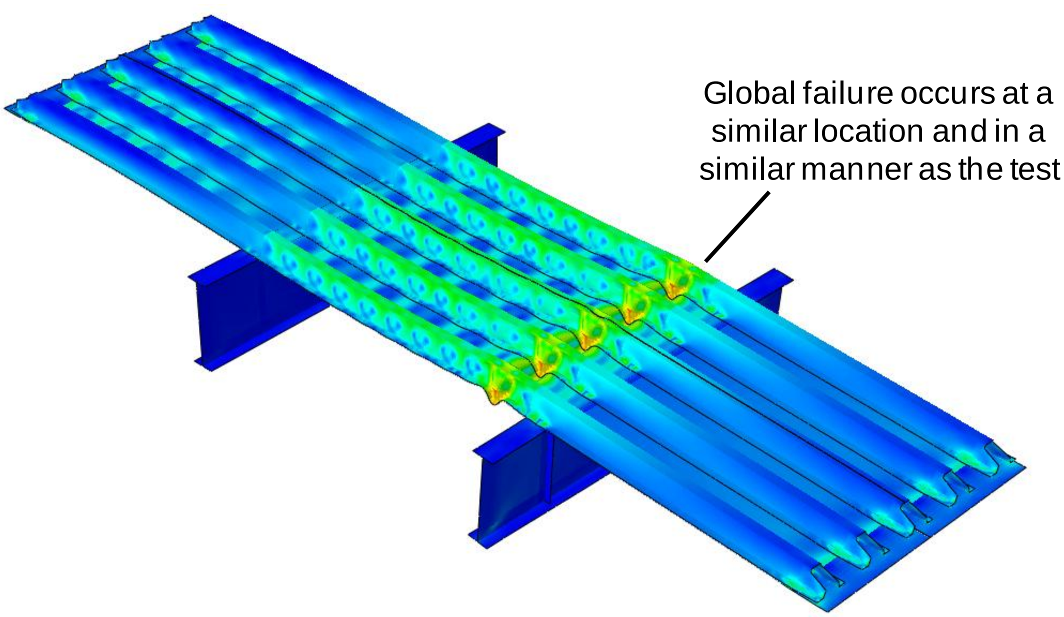


**Figure 4: Test panel FEM global failure mode**

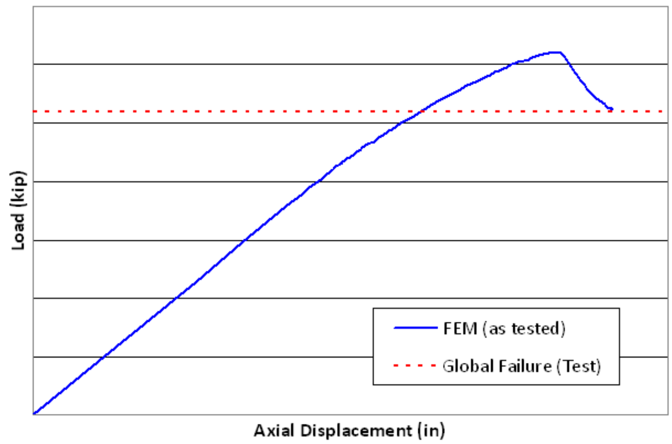


**Figure 5: Load-displacement curve for test panel FEM**

The FEM overpredicts the test failure load by 19.6%. Material damage is not simulated with the as-tested FEM, which may contribute to the overprediction. To take into account the FEM overprediction, a knockdown factor of 0.836 is applied for all load capability calculations and for all configurations tested.

The varying degrees of damage (outlined in Table 1) affected the structural capability of the FEM, but positive fail-safe margins are maintained for all damage conditions considered. A negative margin was calculated for the configuration involving cracks in multiple stringers, although an augmented FEM with the same damage condition showed positive margins. This indicates that the negative margin was dependent on the panel size, and was therefore disregarded, as positive margins were shown for the augmented panel FEM. The fail-safe margin summary is shown in Table 2.

The findings from the analyses for the different damaged configurations contributed to flight rationale by adding confidence that moderate levels of undetected or new damage to the STS-133 Intertank would likely maintain positive fail-safe margins.

In this paper, additional details of the finite element analyses and test-analysis correlation for the stringer panel compression test will be presented. The analyses and results will be discussed as they related to the development of the flight rationale for STS-133.

**Table 2: Fail-safe margin summary**

| Study | Fail-Safe Margin |
|---|---|
| As-tested panel configuration | N/A (test baseline) |
| Flight-like panel configuration | +0.13 |
| Flight-like panel configuration with 7.3-inch cracks in both feet of the middle stringer extending to the first rivet | +0.15 |
| Flight-like panel configuration with 12-inch cracks in both feet of the middle stringer | +0.16 |
| Flight-like panel configuration with 7.3-inch cracks in both feet of the middle three stringers | -0.26 |
| Flight-like panel configuration with short radius blocks on all stringers and no cracks in any stringer feet | +0.13 |
| Flight-like panel configuration with "foot-down" imperfection applied to the ends of the stringers | +0.14 |
| Augmented flight-like panel configuration (pristine) | +0.12 |
| Augmented flight-like panel configuration with 7.3-inch cracks in both feet of the middle three stringers | +0.10 |

## References

1. "Intertank Formed Skin/Stringer Panel Compression Test," MMC-ET-SE63-4, Lockheed Martin Manned Space Systems, July 1996.

2. "I/T Skin/Stringer Stability Test Article," Drawing #80900203064, Martin Marietta Michoud Aerospace, Released March 31, 1995.

3. "Test Fixture - I/T Skin/Stringer Stability," Drawing #97M22728, Martin Marietta Manned Space Systems, Released July 29, 1995.

4. Anon. (2009): *ABAQUS Analysis User's Manual: Volumes I-VI, Version 6.9*, Dassault Systèmes Simulia Corp., Providence, RI.

## Acknowledgement

This work was sponsored by NASA under contract NNM07AB03C with the Boeing Huntsville Design Center.